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CO-GENERATION AND OPERATING NETWORK CELLS

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ABSTRACT

In Denmark several thousands of generators are connected to the distribution system (10 kV and 0.4 kV). The production from these generators many times exceeds the load. The generators can be divided into two types, Wind turbines and CHP generators. These generators have one thing in common, the power system they are connected to, has never been designed to accommodate so many generators. In Denmark we now expect a third type of generators: the micro-generators. This time we want to be prepared. Denmark therefore now participates in a lot of research and full scale demonstration projects. A key concept in along these lines is the "Network Cell".

INTRODUCTION

The first oil crisis 1973-74 had a severe impact on the Danish economy. Denmark was – together with Japan – the country in the world which was most dependent on imported energy. Denmark imported as much as 99 % of all energy used.

Furthermore, the energy was used very inefficiently. There was a waste of energy. Pollution such as NOx and SO2 exceeded the sustainable limits.

Today, some 30 years later, the situation has been changed radically. Denmark is now the only net-exporting country in EU of oil and gas and has a very low energy consumption per unit GDP. Measured as energy use per GDP, Denmark uses much less energy than Poland and only countries as Japan and Switzerland can compete.

Denmark also has the highest share of electricity from new renewables – that is electricity produced on renewable energy other than hydro power. Almost 30% of Denmarks electricity comes from wind power and biomass.

This does not mean that coal has been abolished. It is still a major source in the large combined-heat-and-power-plants. But the coal is used the most optimal way – Danish coal plants are among the most efficient in the world. The emission of NOx and SO2 are minimal.

To obtain these results, Denmark has been granted a little bit of luck, but far-reaching policies have also been adopted to bring Denmark in the international elite with regard to energy efficiency.

The result is that Denmark has successfully de-coupled economic growth and energy consumption. Since 1980 the Danish GDP has grown by 56%, while the energy consumption has stagnated (2% higher in 2004 than in 1980).

It is notable that the total emission of CO2 has declined by as much as 35% in the same period. Thus, for each GDP unit the emitted CO2 is reduced by much more than half in the course of just 25 years.

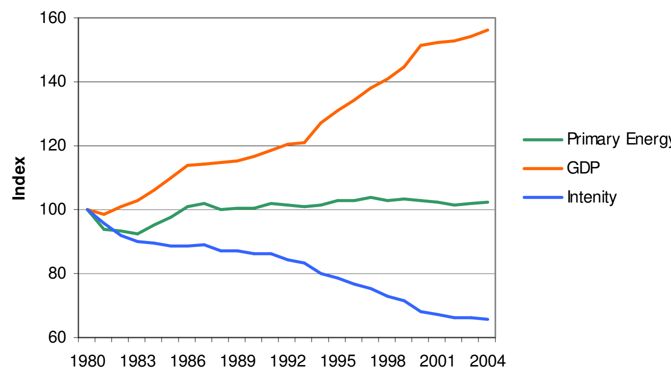

Figure 1. Energy efficient economy

Very few countries can show a similar development. For the same reason Denmark has one of the most ambitious targets for CO2 reduction in the Kyoto agreement.

This sustainable path is paved by the following three explanatory factors, for de-coupling energy consumption from economic growth:

- District Heating and CHP
- Energy Savings
- Renewable Energy (Wind and Biomass)

LEGAL FRAMEWORK SUPPORTING CHP

By using the CHP system we reduce fuel consumption by up to 30% and increase the net efficiency of fuel from 40 to 90 %. I think we in Denmark have one of the most efficient plant in the world. One of our plants has a net efficiency at 94%.

The legal framework for supporting CHP, consists of the following elements:

- Electricity Supply Act (1976)
- Gas Supply Act (1979)
- Heat supply Act (revised in 1990), introduced energy planning
- Voluntary agreements between government and the energy sector

The Heat Supply Act has been most important for development of CHP in Denmark:

- Places an obligation on municipalities to ensure development of CHP projects in District heating areas above 1 MW of heat capacity

- Ministry of Energy can issue guidelines for CHP planning (country is divided into heat supply districts)

- Municipalities have the right to impose compulsory connection to DH networks and to forbid new electrical heating installations in DH areas.

- Regulation of heat and electricity prices by pricing committees under the Ministry of Industry and Trade

The Electricity supply Act (amended in 1998):

Ensures obligation of utilities to buy surplus power from CHP installations against a price covering both short-term as long-term marginal costs

THE DANISH HEAT PLANNING SYSTEM

The system (adopted in 1979) aimed at planning of large investment projects connected to the introduction of natural gas and utilisation of surplus heat

The country was divided into heat supply districts, based on available options of heat supply and individual gas supply

Responsibility for heat planning has been placed on municipal level (since 1990), state has supervisory role

Planning phases in Heat Supply Act:

- Mapping phase, description of current status
- Proposal phase, outline of future options
- Planning phase, identifying least cost options and project development
- Project phase, implementation of planned project

In revision of the Act, a follow-up phase has been included (surveillance, adjustments and connecting up)

CHANGING THE STRUCTURE

In the 1980'ties Denmark had a traditional structure for both heat and Power production. Most of the production was coming from large power plants. Many were located close to the big cities in Denmark.

Figure 2. Centralized structure

During the 1980's Denmark started to decentralise the heat and power production, by erecting a large number of minor plants all over the Country. Still based on combined production of heat and power. But they were located close to the consumers in order to use the heat in local District Heating system.

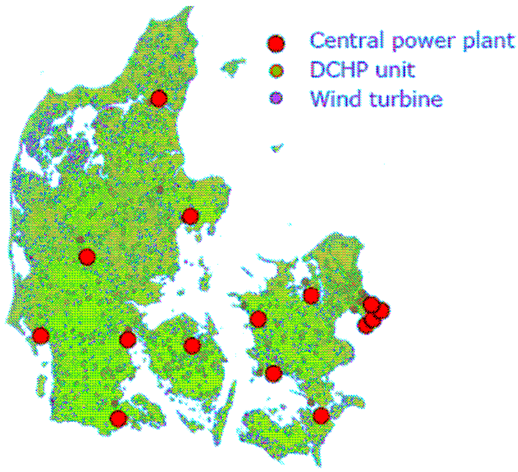

Figure 3. De-Centralized structure

Figure 3 shows the result of this development. All the orange dots are representing the decentralised CHP-plants. Blue dots are wind turbines which is an integrated part of today's energy production.

Figure 4 gives picture of the present situation in the Western Danish Power System.

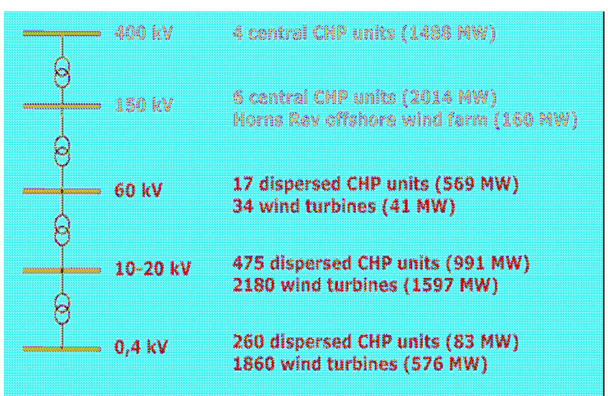

Figure 4. Generators connected to the different voltage levels in the Western Danish Power System 2007.

Figure 5 shows the development in capacity and load in the period from 1990 to 2015. The figure shows also that the production from the decentralised CHP units and the wind turbines connected to the distribution system can cover the load.

IMPACTS ON THE POWER SYSTEM

The utilities in Denmark was not and are still not ready to cope with this situation in their networks. Today 10 central units can be connected to the transmission level, and many times at least two must be connected because of short-circuit power problems (HVDC lines).

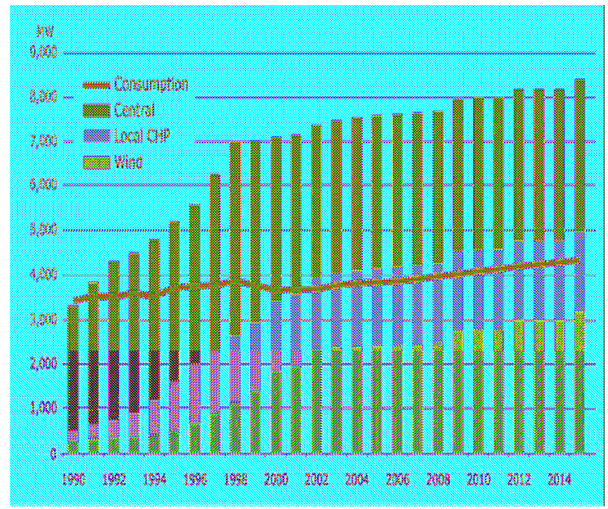

Figure 5. Capacity and load in the period 1990-2015

This is a list of operational and security problems experienced so far:

- Operational problems
    - Maintaining system balance between production and consumption is more difficult and more expensive
    - The TSO must counterbalance increasing reactive power imbalances
    - Voltage problems in local grids with more than average share of DG
- Security problems:
    - Local grids must be reinforced to maintain normal N-1 security
    - Security analyses have become less accurate due to missing information on local generation and unpredictable wind power
    - Protection trips local generation after distant faults
    - Traditional under-frequency load shedding schemes will disconnect both load and generation
    - More complicated and time-consuming restoration after fault

So far the transmission system has been the cornerstone in the Danish power system, but it is difficult to see how this could continue with the number of generators connected to the distribution networks. The TSO in Denmark have therefore adopted Frank von Overbeek's idea of dividing the power system into a number of "cells". A cell in the Danish concept is for the time being a network connected to one of the supply points on the 132/150 kV network. The peak load in such a cell would be between 50 and 60 MW. The idea is that these cells should provide ancillary services to themselves and maybe other cells, such as black start capability, balancing power etc.

The TSO in Denmark has started a pilot project according to these ideas in the Western part of Denmark. This project has even the ambition to demonstrate concepts such as "dynamic islanding". This pilot project is based on a central controller or "cell regulator".

In the Eastern part of Denmark, you will find the Bornholm power system. This power system has for historical reasons still the capability to go into "planned islanding" and black start the system by use of its own resources. DTU works here together with the European project MORE Microgrids for demonstration similar concepts based on decentralized controllers.

THE BORNHOLM POWER SYSTEM

The island of Bornholm is a Danish island situated just south of Sweden. The ØSTKRAFT Company is the Distribution System Operator on the island supplying more than 27.000 customers.

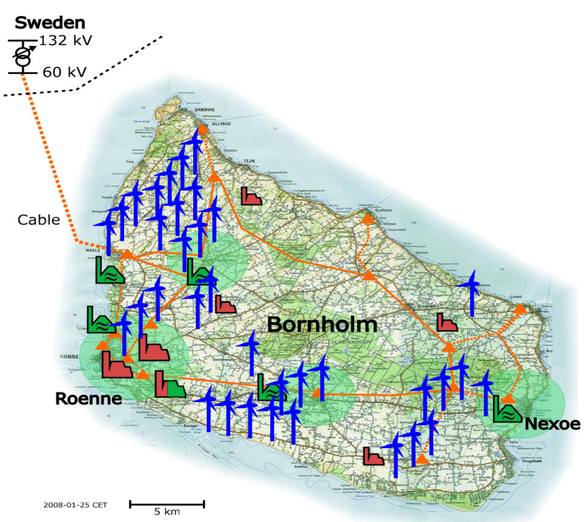

Figure 6. The Bornholm island

A normal distribution system in Denmark connected to a primary 132 kV or 150 kV substation has a peak load between 50-60 MW. The peak load at Bornholm is 55 MW.

In many respects the distribution system on Bornholm has many of the characteristics known from other Danish distribution systems. With respect to areas, load and population Bornholm corresponds to roughly 1% of Denmark.

Wind power covered 22% of the load in 2007, which is above the penetration in Denmark. Its ability to go into planned island mode makes it special and a good "case" for research and demonstration of new technology.

The Bornholm power system consists of the following main components:

- The 132 kV substation in Sweden
- The connection between Sweden and Bornholm
- The 60 kV Network
- The 10 kV Network
- The 0,4 kV Network
- The Load
- The Customers
- The Production Capacity
- The Control Room
- The Communication System
- The 2nd Generation Biofuel Plant
- The District Heating System

The 132 kV substation in Sweden

E-ON is the DSO in the southen part of Sweden. The company owns the equipment in the TOMELILLA and BORRBY substations. From the 132 kV substation TOMELILLA, there is an overhead line to the 132 kV substation BORRBY.

In the BORRBY substation there is two 132/60 kV transformers. One of them supplies the connection to HASLE on Bornholm, the other BORRBY CITY.

The transformer in the BORRBY substation cannot be operated as an OLTC transformer, because the tap changer is fixed.

The connection between Sweden and Bornholm

Energinet.dk is the TSO in Denmark. The company owns the equipment between the BORRBY substation in Sweden and the HASLE substation at Bornholm.

The 60 kV side of the transformer in the BORRBY sub-station is connected to the 60 kV substation HASLE at Bornholm.

The 60 kV Network

Østkraft is the DSO at Bornholm. The company owns the equipment on the Bornholm island. The 60 kV network at Bornholm is meshed and concists of the following elements:

- 18 Substations
- 23 60/10 kV OLTC transformers 219 MVA
- 22 Cables and overhead lines
  - Length of overhead lines 73 km
  - Length of cables 58 km

The 60/10 kV OLTC Transformers keeps the 10 kV voltage to a value around 10.5 kV.

The 10 kV Network
concists of the following elements:

- Overhead Lines 247 km
- Cables 634 km
- Feeders 91
- Average feeders per substation 6

The 0.4 kV Network
concists of the following elements:

- Overhead Lines 518 km
- Cables 1,341 km
- 998 10/0,4 kV Transformer 265 MVA
  - Average kVA/transformer 273
  - Average customer/transfomer 29

The Load in Year 2007 was as follows:

- Peak load 55 MW
- Energy 239 GWh
- Full load hours 4,345 h

The number of Customers are 27,895. 11% or 302 of the customers have a consumption above 100,000 kWh/year. These customers' active and reactive load is measured as 15 minutes average values.

Approximately 30% of the load comes from the 302 customers with a yearly load above 100,000 kWh

The production capacity are as follows:

- 14 Diesel generators (Oil) 39 MW
- 1 Steam turbine(Oil) 27 MW
- 1 Steam turbine(Oil/Coal) 37 MW
- 35 Wind turbines 30 MW
- 1 Gas turbine (Biogas) 2 MW

The 14 diesel units and the 2 steam units are able to control both voltage (10.5 kV) and frequency. The 6 newest wind turbines are able to control voltage, production, ramp rates etc.

The wind turbines generated 53 GWh in 2007. This corresponds to 22% of the load.

The control room is able to set:

- The tap changers at all 60/10 kV transformers
- The capacitors in all 60/10 kV substations
- The voltage reference in the following units
  - 14 Diesel units 37 MW
  - 2 Steam turbines 64 MW
  - 6 Wind turbines 11 MW
- The frequency regulator in the following units
  - 14 Diesel units 37 MW
  - 2 Steam turbines 64 MW
- The production and ramp rates in the wind turbines
  - 6 Wind turbines 11 MW

The main tool at the control room is the Scada System for:

- The 60 kV and 10 kV Network
  (ABB NETWORK MANAGER)
- The 6 Wind turbines (VESTAS Online)
- The 14 Diesel units
- The 2 Steam turbines

The time resolution in the ABB NETWORK MANAGER is 10 seconds instantanous values, 1 minut average values or 1 hour average values.

The time resolution in the VESTAS ONLINE system is 10 minutes average values.

The Communication System
To support the communication between e.g. the relays and the RTU's in the substations, an optical fibre network has been established.

2nd Generation Biofuel Plant
The 2 MW plant "Biokraft" on Bornholm is the largest and most advanced biogas plant with high-tech separation in the world. It provides a yearly CO_2 reduction of 14,000 tons. The plant produces approximately 6,000,000 m^3 Biogas, which generates 16,500 MWh electricity and 8,000 MWh heat.

District Heating
The total heating requirements for Bornholm are approximately 560,000 MWh/Year. Currently, this is

covered by three heating sources: District heating, buildings with electric heating and individual boilers.

The district heating sector of Bornholm is made of five distribution areas. For further information see ref [5].

RESEARCH

This section provides an overview of research and educational activities using the Bornholm power system as a "case". The activities are divided into 5 main subjects.

- Demand Response and Market
- Island Operation
- Wind power Integration
- Experimental Research platform
- Transportation

The overall objective of the research is to develop a smarter low carbon-emission electric power system which can handle an increased share of renewable energy and distributed generation, enable an open market and secure the reliability of supply. Further information regarding the activities can be found in ref [6].

Subject 1: Demand Response and Market

Demand as Frequency Controlled Reserve

This activity investigated the feasibility of demand as a frequency controlled normal and disturbance reserve. The project is done by CET and Ea Energy Analysis and supported by PSO funds.

Subject 2: Island Operation

EU More Microgrids

CET participates in an EU-funded project regarding island operation of distribution systems. Bornholm is used as a demonstration case.

Control Architecture for Intentional Islanding

A PhD project focuses on control architecture of future power systems specifically in relation to transition between normal operation and island operation. Data from Bornholm is used. The project is a part of the Nextgen project supported by Energinet.dk.

Subject 3: Wind Power Integration

More Wind

This activity focuses on the situation where energy from Wind turbines increases, from today's 22% to maybe 40%.

Coordinated Frequency Control

This activity includes a PhD project with the main objective to develop a dynamic model and control scheme implemented in a Power Factory simulation tool, design of active frequency control scheme for the Vestas wind turbines and full scale implementation at wind turbines on Bornholm. This is done by Centre for Electrical Technology and Vestas.

Subject 4: Experimental Research Platform

Dynamic Simulation Platform

A dynamic simulation model of Bornholm is developed using the Power Factory tool and validated.

PowerLabDK

CET has been granted a pre-project in order to concretize an experimental research platform for the future power system. The experimental research platform is expected to consist of laboratory facilities, for tests under controlled conditions and a full-scale demonstration system.

Phasor Measurement Units (PMU)

CET has developed novel measurement equipment, phasor measurement units (PMU's), which with high time resolution and accuracy has the ability to measure voltage angle differences in the power system. Two PMU's are preliminary installed at block 5 and block 6. The installations will be made permanent and an additional PMU will be located in HASLE.

Subject 5: Transportation

Vehicle to Grid and plug-in hybrid cars

The project developes and demonstrate vehicle to grid and plug-in hybrid cars, with the goal to make a very visible showcase for the 2009 Climate Summit in Copenhagen.

Balancing Wind with Electric cars

A PhD project regarding balancing wind power by electric vehicles focusing on fault tolerant control and operation has been suggested. Bornholm will be used as a show case.

POTENTIAL FUTURE ACTIVITIES

This section provides an overview of potential future activities:

- Local online electric power market for real-time balancing and ancillary service provision
- Distribution network operation by use Syncroneous Condensors
- Distribution network on by use of fly wheels
- Physical Virtual Power Plant
- IEC61850 communication
- Demonstration of improved active power control by demand as frequency controlled reserve
- European implementation and demonstration of active distribution network (Ecogrid)

PLANNED ISLANDING

In September 2007 (11/9 to 14/9) the Bornholm Power System was disconnected from the transmission system in Sweden on request from the DSO in Sweden (E-ON). In Figure 7-10 some of the measuring results are shown. During this period the biogas-generator disconnected from the system. The frequency response can be sseen from Figure 8. Figure 10 shows the frequency at Bornholm and in the Nordel system at the same time.

ACKNOWLEDGEMENTS

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CONCLUSIONS

National regulatory framework connected with strong local energy planning aimed at increase of district heating and CHP

Spread of CHP started at heating plants, due to existence of large district heating network. Industrial CHP developed later in connection with subsidies and energy taxes.

A strong planning tool can favourably influence the utilisation of CHP from the beginning.

Danish energy policy is strict, but also partly based on agreements with utilities and other stakeholders.

Nobody expected the success of the CHP initiative, so the utilities was not and are not prepared to connect the many generators in a proper manner.

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BIOGRAPHY

John Eli Nielsen was born in Denmark 1944. He received his M.Sc.EE. degree in electrical engineering from The Technical University of Denmark in 1974 and his Industrial PhD degree in 1976. He has been working for the transmission system operator in Denmark for 25 years. Currently, he is working for The Technical University of Denmark as an associate professor. His experience lies in the area of planning and operation of power systems. He is a member of IEEE and has for many years been the Danish representative in CIGRE Study Committee 39 – *Power System and Control.* *jen@elektro.dtu.dk*

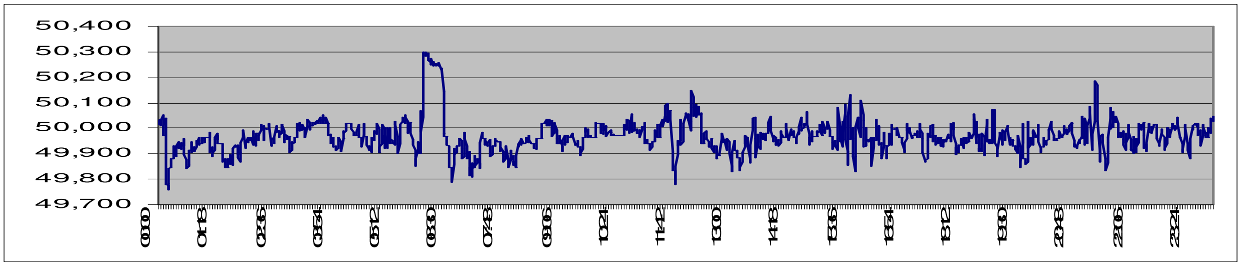

Figure 7. Frequency Wednesday the 12th of September 2007 (1 min average values)

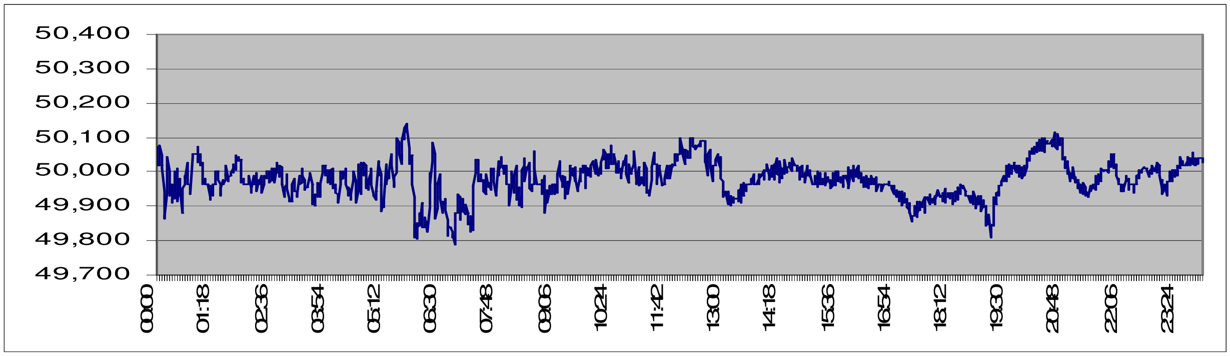

Figure 8. Frequency Wednesday the 12th of September 2007 (20 ms values)

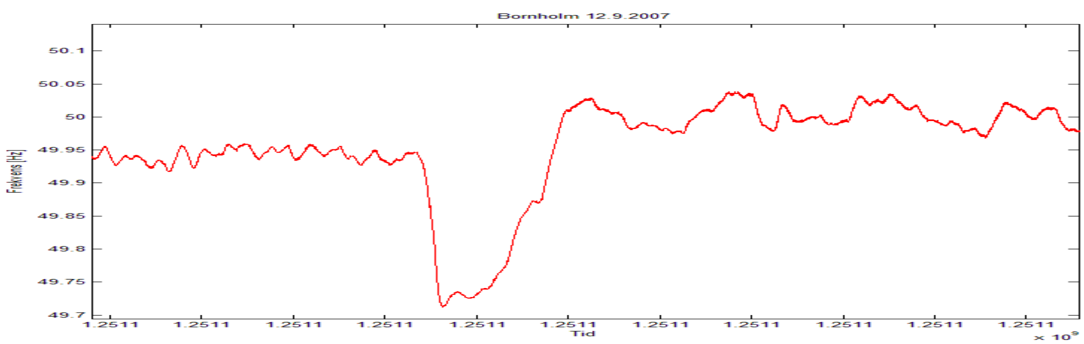

Figure 9. Frequency Friday the 14th of September 2007 (1 min average values)

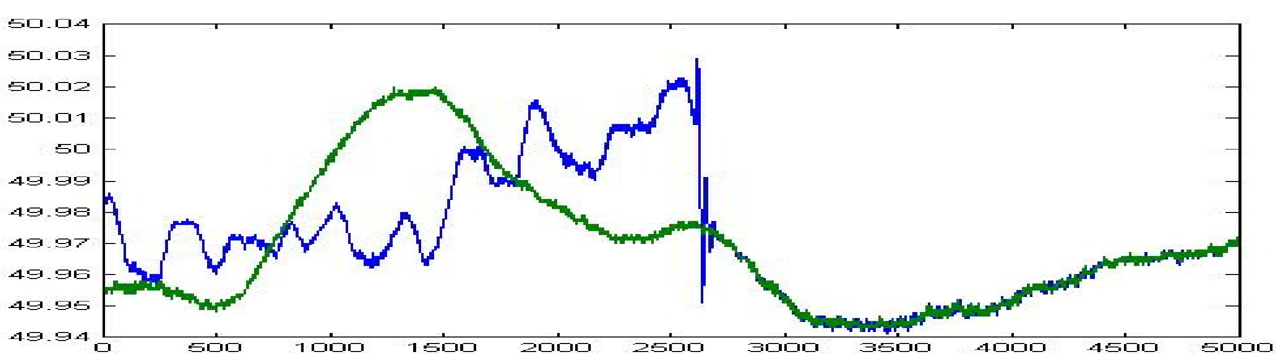

Figure 10. Frequency Friday the 14th of September 2007 (20 ms values)